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APOLLO EXPERIENCE REPORT - GROUND-SUPPORT EQUIPMENT

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16. Abstract <p>This report is a summary of the experience gained in management of the ground-support-equipment and site-readiness activity for the Apollo Program. The discussion is divided into nine representative areas. The first seven sections generally pertain to the design of equipment and facilities, although some operational aspects are examined as well. The organization for ensuring site readiness and the maintenance of ground-support equipment are discussed in the last two sections. Recommendations for use in future programs are given in the areas of design considerations, cleanliness requirements, periodic evaluation of changing requirements, maintenance and overhaul, special test equipment, site-activation schedule coordination, and schematics for ground-support equipment.</p>					
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APOLLO EXPERIENCE REPORT

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APOLLO EXPERIENCE REPORT

GROUND-SUPPORT EQUIPMENT

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SUMMARY

The responsibility for ground-support equipment and site readiness comprised the exercising of management control over two prime spacecraft contractors. This responsibility included providing total capability for vehicle test and checkout at the factories, development centers, and launch sites, and ensuring operationally ready facilities and support equipment for each site/facility/vehicle combination.

To meet scheduled program requirements, unique approaches such as standardization of cables, utilization of common-use equipment, and automation of vehicle checkout were adopted. The experience gained in the management and development of ground-support equipment in the areas of design standardization, design inadequacies, ground power systems, special test equipment, cleanliness and environmental control, automation, common-use equipment, site readiness, and maintenance and overhaul would be beneficial if applied early in future programs.

INTRODUCTION

The responsibility for ground-support equipment (GSE) and site readiness was assigned to an organization within the Apollo Spacecraft Program Office. This organization exercised GSE management control over the two prime spacecraft contractors. Management responsibility encompassed providing total capability for vehicle test and checkout at the factories, development centers, and launch sites, and ensuring operationally ready facilities and support equipment for each site/facility/vehicle combination.

Several aspects of the GSE program are examined in this report. Each aspect was important to the development of the total program and could merit presentation as a separate report; however, a more effective presentation results from combining them into a single report. The discussion of the Apollo GSE program experience is followed by recommendations for use in future programs. These recommendations are not linked to specific problems; instead, the recommendations are based on general practices that evolved and proved to be useful during the Apollo Program.

As an aid to the reader, where necessary the original units of measure have been converted to the equivalent value in the Système International d'Unités (SI). The SI units are written first, and the original units are written parenthetically thereafter.

DESIGN STANDARDIZATION

The GSE systems were designed to support similar vehicle test requirements and procedures at the various checkout facilities and thus provided the capability to obtain a close correlation of test data and to interchange GSE units among facilities. Ground-support-equipment end-item design was standardized to reduce the number of different units, to reduce the GSE manufacturing time, and to reduce the GSE and spacecraft test time. Standardization of the GSE allowed a reduction in the number of spare parts required and a reduction in the operating personnel training requirements. Further, the GSE system-standardization approach permitted maximum use of GSE units among checkout facilities and was an important asset in meeting the demanding Apollo schedules.

Computerized Control Station

The complexity and completeness of Apollo systems checkout necessitated a highly complex network of GSE at each test site. To control and monitor this network, GSE units were electrically connected to centrally located computerized control stations (fig. 1). Standardization of calibration data and some computer programs was



Figure 1.- Acceptance checkout equipment (ACE) control room.

possible because the networks at the various test sites were similar. This standardization, coupled with test requirements and procedural similarity, permitted a close correlation of test data from the factory to the launch pad. Thus, the probability of detection of any spacecraft systems degradation during preflight testing was enhanced.

Electrical Cables

Minimization of the types of electrical signals required to control and monitor the performance of GSE permitted standardization of interconnecting cables. This standardization resulted in the procurement of two basic cable types.

1. A cable containing 60 individually shielded conductors, with insulated shields
2. A cable containing 38 conductors, consisting of 19 individually shielded twisted pairs

During manufacturing, the cable types were terminated in 61- and 62-pin connectors. In a single A-size drawing (21.6 by 28 centimeters (8.5 by 11 inches)), the variations of a specific cable type were documented. Dash numbers were assigned to specify different lengths and connector types (figs. 2 and 3). The use of standard cable types resulted in a significant reduction in cable fabrication time and cost. Without this standardized design, it would have been difficult to deliver the electrical GSE cables (approximately 25 000 of all types) in time to support Apollo testing.

Electrical Terminal Distributors and Patchable Connectors

Electrical signal routing among GSE units (from GSE to facility and from GSE to spacecraft) was accomplished by means of cables that were connected to electrical terminal distributors (ETD) units (fig. 4). A patchable connector, developed specifically for the Apollo Program to permit interchange of signals within a cable, made ETD design standardization possible (figs. 5 and 6). The patchable halves of these connectors were mounted on removable bulkheads in standard equipment racks. This arrangement provided a prepatch capability and interchangeability. Electrical signals were routed by cable patching within the ETD.

Because of similarity and close manufacturing surveillance, qualification testing was accomplished on a single rack of the ETD; other racks were qualified by similarity. Parts were purchased in large quantities, a procedure that minimized unit costs. Standardized design of ETD units allowed additional savings through a reduced spare parts inventory.

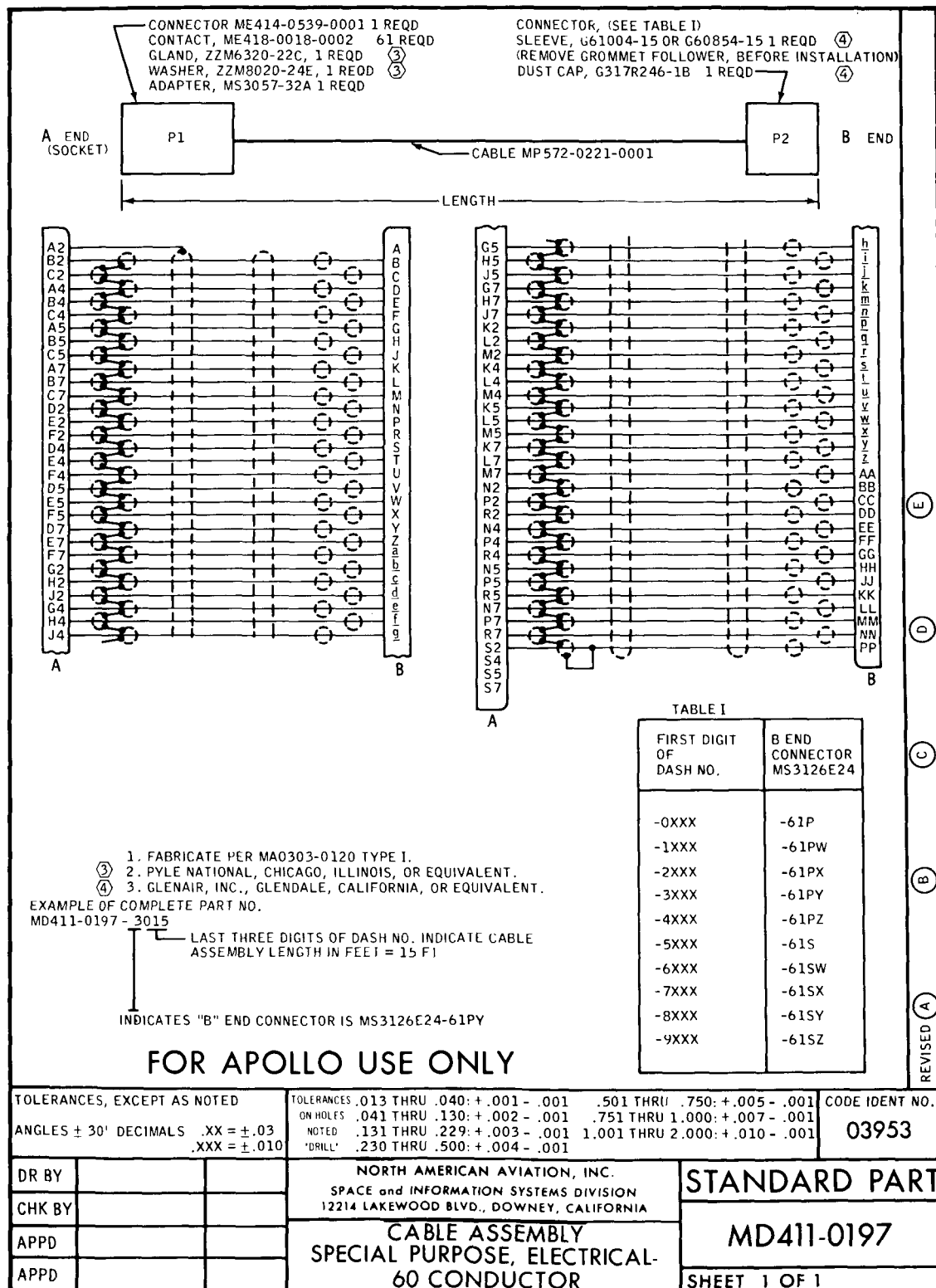


Figure 2.- Standard 60-conductor cable.

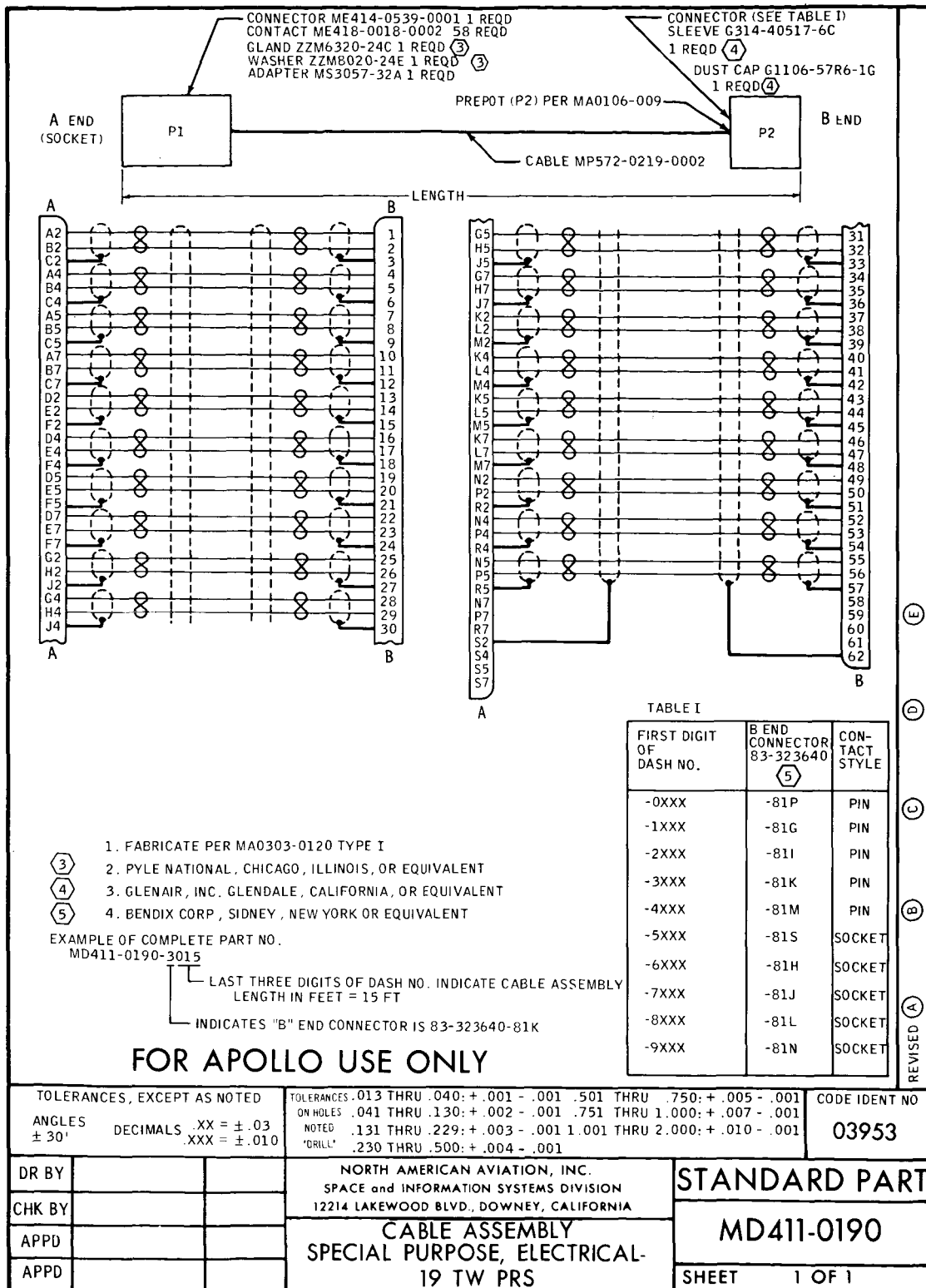
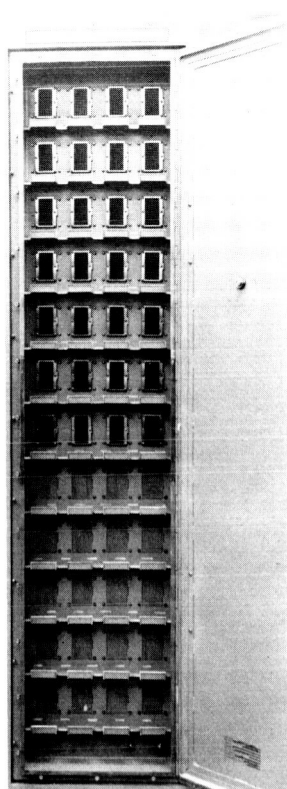
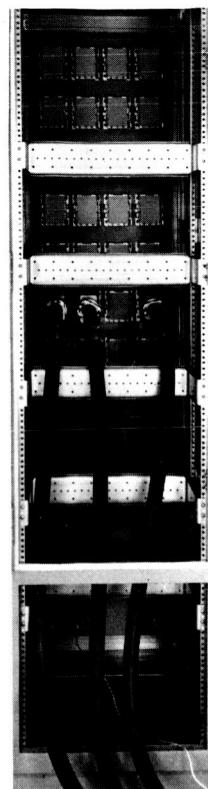


Figure 3. - Standard 38-conductor cable.

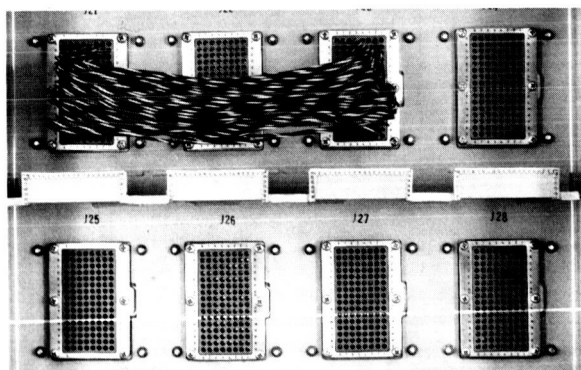


(a) Front view.

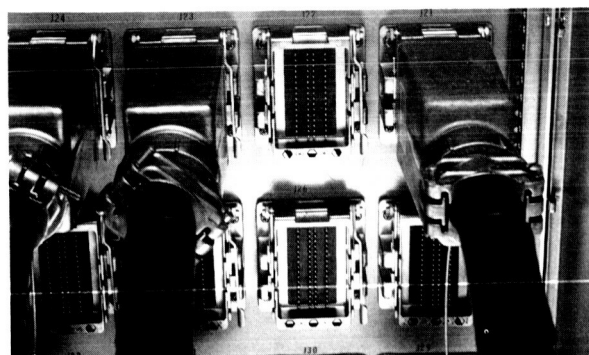


(b) Rear view.

Figure 4. - Electrical terminal distributor.



(a) Patchable configuration.



(b) Cable installation.

Figure 5. - Standardized connector installed.

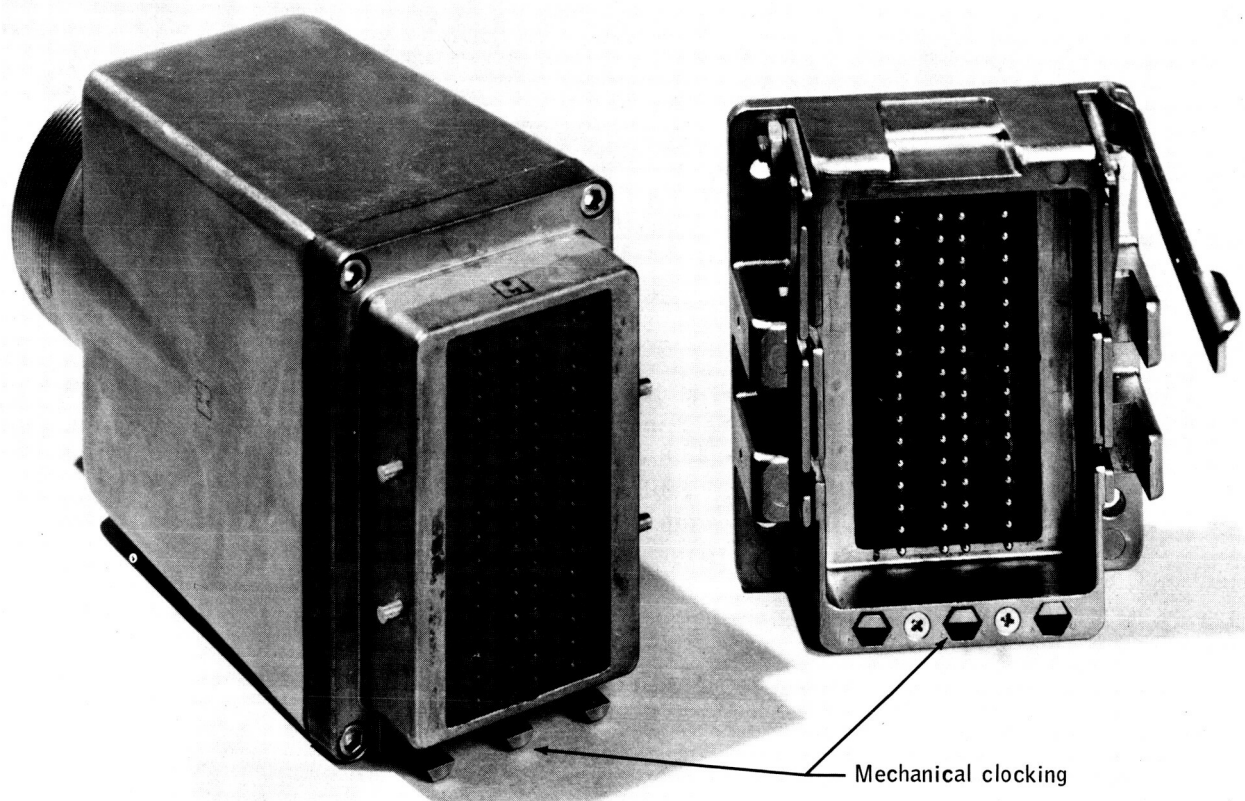


Figure 6. - Standardized connector.

Fluid-Servicing Equipment

The fluid-servicing requirements differed at each test site. In general, only pressure checks, leak checks, flow checks, and water servicing were performed at the manufacturing plants and the development areas. However, the GSE designed for a complete servicing operation at the launch site was used at all test areas to limit the number of designs. Portability was a primary consideration in standardizing fluid hardware.

DESIGN INADEQUACIES

After the GSE became operational, certain design inadequacies were evident. These inadequacies, identified in design reviews, in equipment failures, and in failure mode and effects analyses, necessitated that protective devices be incorporated, that constraints be reevaluated, and that GSE systems be simplified to achieve acceptable operational performance.

Cryogenic Simplification

The design of the cryogenic servicing system was influenced by weight restrictions on the mobile service structure. These restrictions, in addition to a remote-control requirement, led to the development of a system that used stowage tanks, pumping units, and vacuum-jacketed lines to convey liquid oxygen and liquid hydrogen from the ground to the spacecraft (91-meter (300-foot) level). However, the heat leak over this distance was greater than had been anticipated; therefore, a hydrogen subcooler was installed. This improvement provided, at best, a marginal transfer system.

The weight restriction was eliminated when a counterbalance was added to the mobile service structure. The remote-control requirement was deleted in favor of local control with pad-clear and remote monitoring. Because of these changes, the entire cryogenic servicing system was replaced with portable cryogenic tanks (fig. 7) and a simplified control system. The tanks were filled, then lifted (by means of an elevator) to the appropriate spacecraft level.

Use of the portable-tank concept resolved the heat-leak problem and enabled the removal of stowage tanks, transfer units, hydrogen subcooler, and vacuum-jacketed lines. Use of this concept also permitted local control at the spacecraft level.

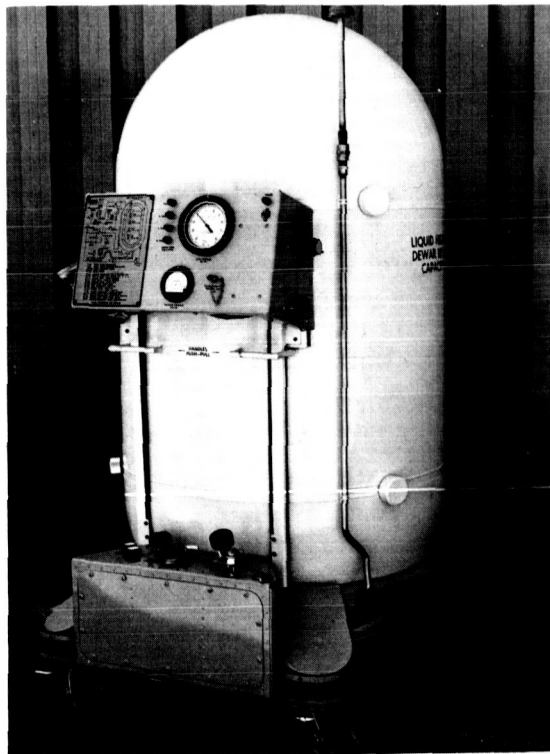


Figure 7. - Cryogenic tank.

Protective Devices

Protective devices were incorporated after initial production of the units. For example, switchguards were installed on approximately 250 units to prevent inadvertent switch actuations, and shatterproof lenses were installed to protect personnel from flying glass and to protect readout devices from damage.

Checkout Requirements

Six factory test stands were planned to support separate command module and service module checkouts. Subsequent analysis verified the feasibility of performing these checkouts in a mated configuration using integrated stands. Consequently, the number of test stands required was reduced to four (fig. 8).

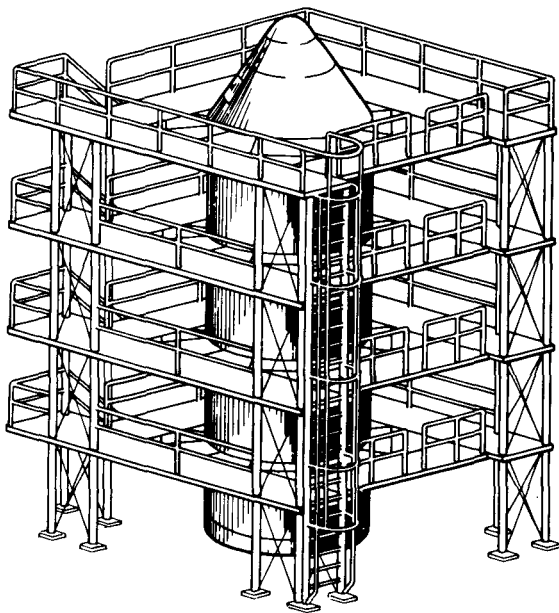


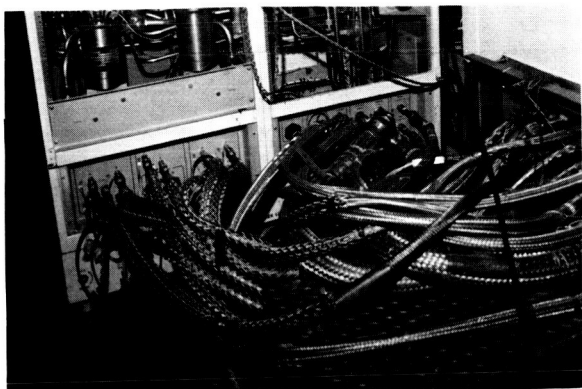
Figure 8. - Integrated checkout station.

Flexible Hoses

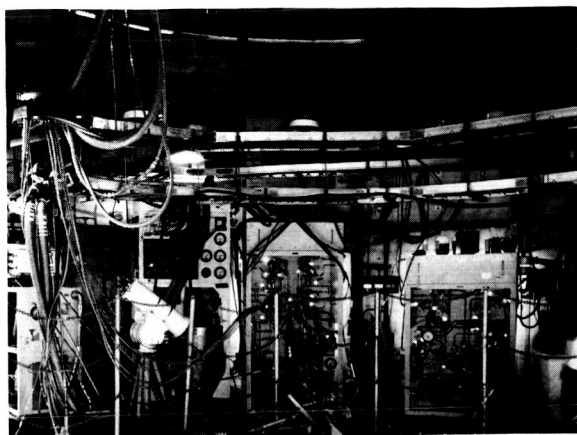
During initial site activation, hardlines could not be routed to the GSE because location was not defined. Hardlines were routed to bulkhead interfaces, and flexible hoses were used to connect bulkhead interface, GSE, and spacecraft fittings (fig. 9). The use of hoses in this manner resulted in the following problems.

1. Internal flaking caused contamination of the fluid.
2. The requirement for periodic proof-pressure testing incurred additional time and cost.
3. The use of incorrectly pressure-rated hoses created safety hazards.
4. The interchange of incompatible hoses among fluid sources created system contamination and hazardous conditions.

Because of these problems, many hoses were replaced with hardlines (fig. 10).

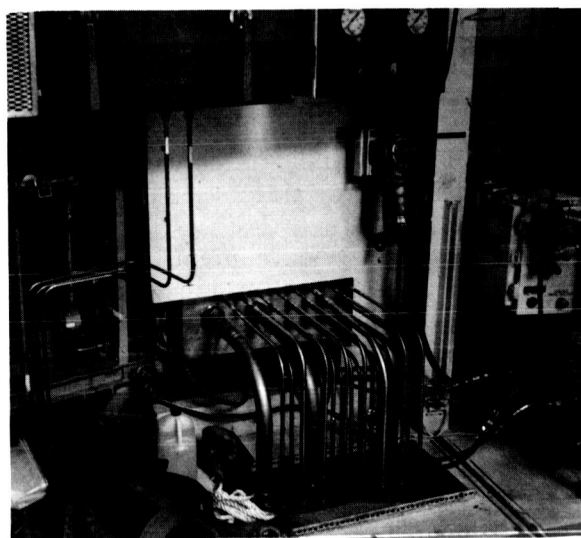


(a) Flexible hose at console.



(b) Flexible hose routing.

Figure 9. - Flexible hoses.



(a) Console installation.



(b) Equipment routing.

Figure 10. - Hardlines.

Electrical Connectors

Many testing hours were lost because of improper procedures in the mating and demating of electrical connectors. To avoid this problem, a mate and demate connector checklist was implemented. Connections required for specific tests were controlled by installing plastic connector locks that were verified by quality control.

Electrical Problems

A spacecraft system/GSE assessment revealed that current and voltage levels in excess of spacecraft specification limits could result if electrical GSE was improperly adjusted or operated or if a GSE control component failed. Results of analysis indicated that such a condition would overstress spacecraft components and could go undetected in subsequent tests. Voltage- and current-limiting devices (such as circuit breakers, fuses, diodes, and resistors) were added to correct this condition.

Overpressure Problems

Many GSE relief valves were not sized properly to carry the quantity of fluid that would be available if an upstream regulator failed. A regulator failure would allow pressures at the spacecraft interface to exceed specification limits. Therefore, properly sized relief valves were added.

GROUND POWER SYSTEM

During the conceptual stages of the Apollo GSE design, direct current (dc) was selected as the type of primary power source to be used for control and monitor functions. This selection was influenced by three important factors that greatly simplified the detailed design of the GSE end items. First, many commercially available electrical components were designed to use 28 volts dc. Second, dc control signals did not require the complex routing, grounding, and shielding techniques that were required by alternating-current (ac) control signals. Third, and most important, the GSE dc control system was more compatible with the spacecraft because the primary spacecraft power source was also dc.

The use of 60- and 400-hertz ac power was limited to pumps, heaters, motors, lighting, and ac-to-dc conversion equipment (fig. 11). This arrangement resulted in cheaper, commercially available hardware and simplified design.

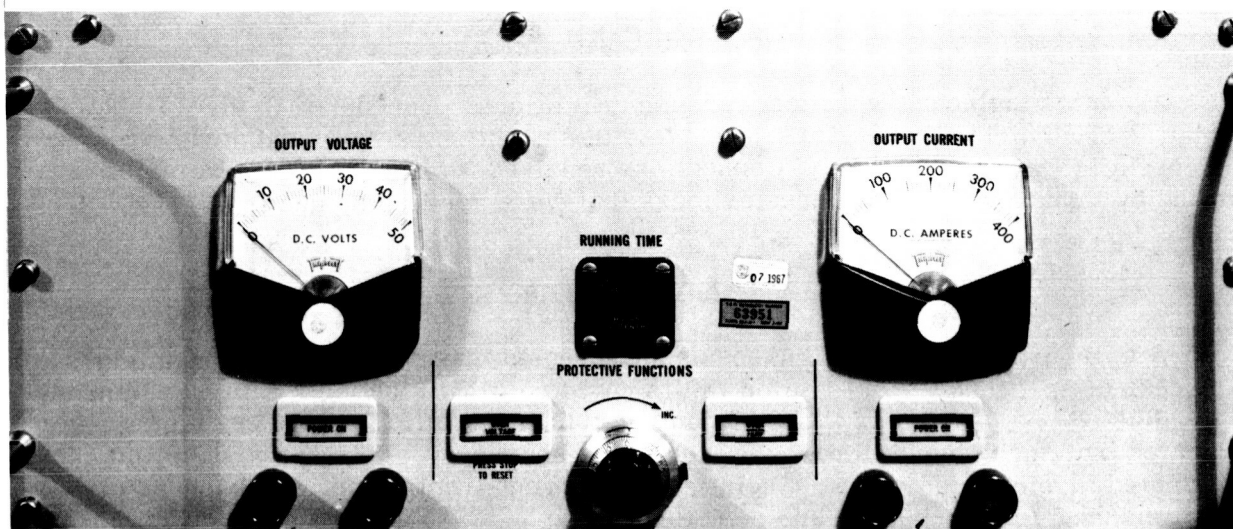


Figure 11. - Alternating-current to direct-current converter.

Direct-Current Ground Power System

Direct-current power was provided by solid-state power supplies that had variable outputs as great as 40 volts at the launch pad (fig. 12). Each power supply had an associated backup system that consisted of batteries, battery chargers, and, for initial control voltages, a small dc power supply that was powered by ac. The power supplies were centrally located at the base of the mobile launcher and at the base of the mobile service structure. Power was distributed to the spacecraft and the GSE through large (350 to 500 MCM¹) copper cables. Power was provided to acceptance checkout equipment (ref. 1), command module buses, lunar module buses, and other GSE that supported launch operations and checkout. Six power supplies were located on each mobile launcher, and two were located on the mobile service structure. Control and monitor functions were integrated into a system that interfaced with the remote-control stations.

Alternating-Current Ground Power System

Because 400-hertz ac power was not available as a facility source, GSE units that would supply this power at the launch pads were manufactured. Initially, only three types of GSE required 400-hertz power. Two types were later deleted, but the use of 400-hertz power was continued for the third type because of weight restrictions imposed on the mobile launcher at the spacecraft level. The weight restrictions were removed later, and a conversion to 60-hertz power was authorized on the remaining GSE model as a cost tradeoff instead of modifying the 400-hertz power supplies that had undergone excessive failures.

¹MCM = cross-sectional area given in thousands of circular millimeters.

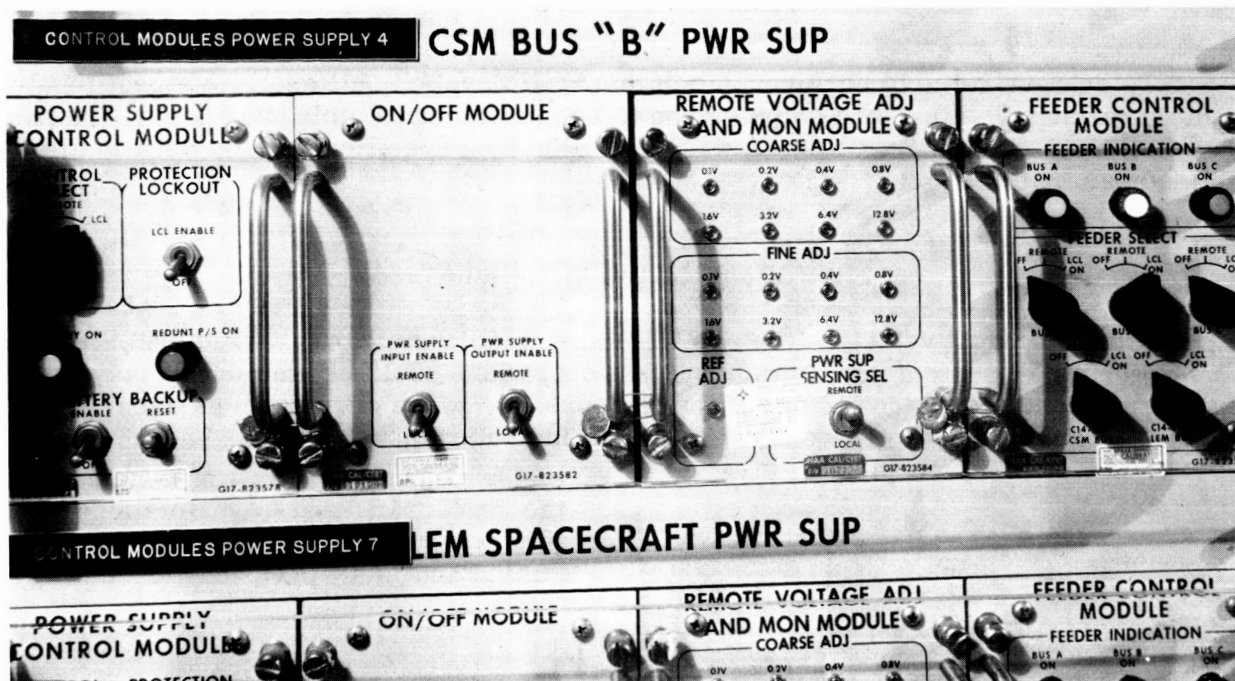


Figure 12. - Direct-current power supplies.

SPECIAL TEST EQUIPMENT

The need for factory test equipment that could be produced expeditiously and without formal GSE controls resulted in the fabrication of special test equipment. The equipment was factory built, and good commercial standards and available off-the-shelf components were used. Special test equipment was used on an interim basis to fulfill the need for GSE created by expanded test requirements. The hardware was approved as "one of a kind," and no spares were provided. Some special test equipment was built to GSE documentation standards and was identified later as GSE for use on subsequent vehicles.

Occasionally, the lack of adequate controls at the factories allowed fabrication of hardware from sketches, layouts, and load diagrams. The hardware configuration was not formally documented. This lack of documentation made the hardware configuration unacceptable for follow-on tests and made data correlation difficult.

CLEANLINESS AND ENVIRONMENTAL CONTROL

To achieve reliable performance of the Apollo system, all operations that involved vehicle buildup, testing, and shipping had to be performed in a cleanroom environment. The GSE fluid-systems cleanliness was controlled by a specification that defined allowable contamination levels.

Environmentally Controlled Areas

After the basic vehicle structure was assembled and cleaned, structural cleanliness during subsystem installation and test operations could be maintained only in an environmentally controlled area in which personnel wore cleanroom garments (fig. 13). Further controls were exercised by logging removable items brought into

the spacecraft, by limiting access to the spacecraft, and by maintaining positive pressure in the spacecraft crew station and in all pressure vessels.

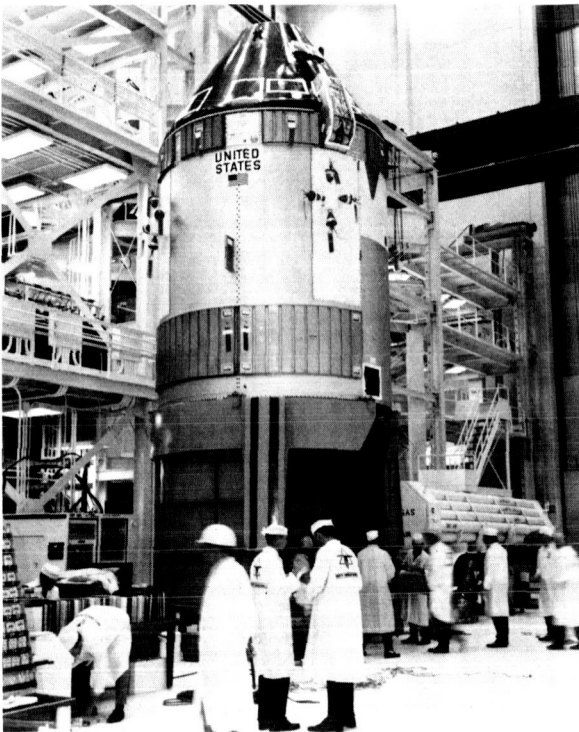


Figure 13.- Cleanroom garments.

had to be accomplished expeditiously within the accuracy ranges necessary to ensure maximum safety and mission success. Spacecraft subsystems were verified simultaneously and in parallel with some manufacturing operations. Many checkout and servicing operations were automated to reduce test time and to meet required schedules.

Fluids

The spacecraft fluid-systems design specification required that the system be free of particles larger than 100 micrometers. The fluid-servicing GSE was designed and maintained to exceed this stringent cleanliness requirement. Particulate contamination was a constant problem because of the necessity of using flexible hoses, which contaminated the fluid, and the inability to perform in-place cleaning because of system design. The contamination problem was minimized by installing filters at the vehicle interface.

AUTOMATION

Because of demanding Apollo schedules, spacecraft test activities

Automated Checkout

The electrical checkout and fluid-servicing functions for the Apollo spacecraft subsystems were commanded and monitored from a remotely located computerized control room (fig. 1). Within this control room, computer routines were used to apply spacecraft subsystem test stimuli. Related spacecraft responses were displayed on subsystem consoles and monitored for out-of-tolerance conditions. Subroutines were used for fault isolation tests during troubleshooting operations. The automation of factory test and launch control sequences was instrumental in achieving a well coordinated and expeditious spacecraft checkout and launch operation (ref. 1).

Automated Servicing

Safety and operational considerations dictated that the fluid-servicing equipment be designed for both local and remote operation. Control panels for local operation are shown in figures 14 and 15.



Figure 14. - Fuel control panels.

When the program entered the operational phase, it became evident that total remote operation of the servicing functions was not practical because the majority of the effort was expended in preparing for the test. Important operations that were unsuitable for automation were the installation of filters, the connection of equipment to the spacecraft, the performance of leak checks, the verification of proper GSE setup, and the

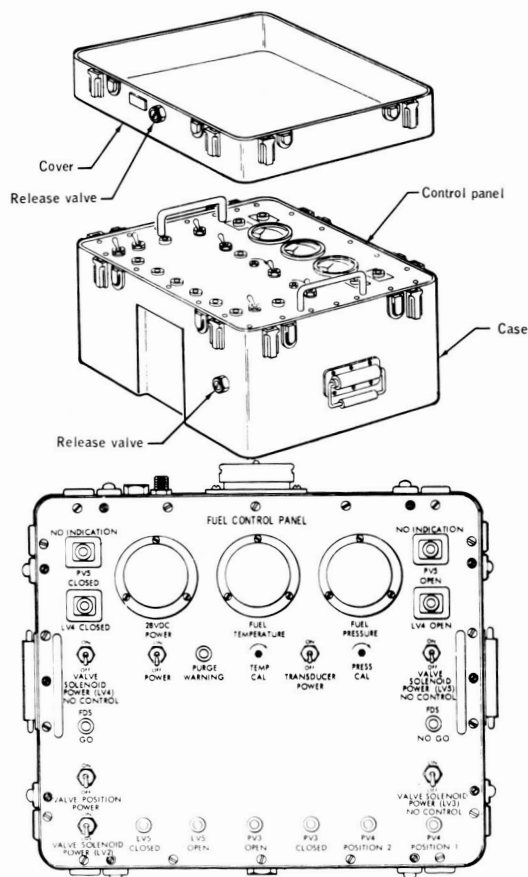


Figure 15. - Fuel control panel details.

sampling of fluids. By rescheduling tasks during nonhazardous operations and by changing some of the requirements, most of the servicing was accomplished locally, and the parameters were displayed both locally and remotely in the computerized control room.

The increase in acceptance checkout equipment (ACE) control room displays progressed to the point where the memory capacity of the ACE computer had very little growth potential. This limitation in ACE memory would result in data being provided to the test operators on a delayed basis by posttest data reduction, which would be especially unfeasible when data analysis from one test was required before the start of the next test. In 1968, the ACE memory capacity was increased by 24 000 memory bits to permit planned operations and allow for future growth in ACE control room displays.

COMMON-USE EQUIPMENT

The use of similar spacecraft hardware, propellants, and checkout techniques made the sharing of GSE possible. The sharing concept eliminated duplication of equipment design and fabrication by separate contractors when performing similar functions. Because the operating characteristics and location of the common-use GSE were not identical, the following three equipment categories were established.

1. Category A-1: Equipment in this category was unmodified hardware that fulfilled the requirements of more than one contractor. The developing contractor operated the hardware and maintained configuration control.
2. Category A-2: Equipment in this category was the same as category A-1 equipment except that the using contractor operated it. Modifications were fabricated by the developing contractor and installed by the user.
3. Category A-3: Equipment in this category was designed for multiple applications. Modifications to the original designs were necessary for specific uses. The using contractor had total responsibility for the hardware.

MANAGEMENT OF GROUND-SUPPORT EQUIPMENT AND SITE READINESS

Project management of GSE was not limited to design, fabrication, and manufacturing schedule reviews. Project management also encompassed the GSE allocation, priority establishment, integration, installation, and verification at each manufacturing, test, and launch site.

Because of stringent Apollo schedules, GSE was manufactured concurrently with test- and launch-site construction. Thus, a GSE/site-activation organization had to be formed quite early in the program. Specialists were selected to manage the site activation at all manufacturing, test, and launch facilities. A composite evaluation was made of problems common to all sites (such as fluid cleanliness). The status of

site readiness was assessed by the NASA Lyndon B. Johnson Space Center (JSC) (formerly the Manned Spacecraft Center (MSC)) in monthly management review meetings. When launch, vehicle, and test schedules changed, specific "need dates" for GSE end items changed. These changes were reflected in the GSE production plans and delivery schedules.

After initial site activation, site readiness for follow-on vehicles was determined in an MSC and contractor review meeting conducted just before vehicle arrival for test or launch. This effort included a physical inspection of the sites and associated GSE. All pertinent documentation, such as modification-installation status reports, open engineering orders, quality and reliability control records, and interface control document revisions, was reviewed in detail for open work.

MAINTENANCE AND OVERHAUL

Readiness of GSE was ensured by periodic calibration, overhaul, or component replacement. Overhaul candidates were primarily in the field of servicing equipment. In the Apollo Program, servicing equipment had backup or redundant units that enabled the performance of orderly, timely overhauls with no launch constraints.

Contractor proposals for GSE overhauls were based on usage, age, or failure history. These proposals were evaluated to determine the extent of overhaul. The following considerations were included.

1. Use and environment of equipment
2. Expense of overhaul compared with expense of end-item replacement
3. Availability of backup units to support prime units
4. Availability of spares
5. Review of the failure history
6. Periodic replacement of components already authorized in age/life component-replacement criteria and in routine preventive maintenance schedules

RECOMMENDATIONS AND CONCLUSIONS

Recommendations

The following material is presented primarily as recommendations for use in future programs.

Design standardization. - Design standardization encompassed the use of standard cables and patchable connectors that provided interchangeability and versatility among the ground-support-equipment units so that vehicle requirement changes could

be accomplished. Standardization of calibration data and some computer programs permitted a close correlation of test data from the factory to the launch pad. Ground-support equipment was standardized to reduce the number of different units, to reduce the ground-support-equipment manufacturing time, and to reduce the ground-support-equipment and spacecraft test time. Portability was a primary consideration when fluid-servicing and test hardware were standardized.

Design inadequacies. - Design inadequacies may be limited if the most severe requirement is selected as a design base. This selection would have the net effect of limiting the number of designs, reducing spares, providing for interchange of hardware between sites, limiting the total end items, and developing standard operating techniques.

The use of flexible hoses as permanent installations should be avoided. However, hoses are valuable for temporary connections and for use where cleanliness is not a prime consideration.

Controls should be instituted for mating or demating electrical connectors. Proper connections can be maintained if destroy-to-remove plastic connector locks are used. Another consideration is an electrical series circuit that is routed through all required connections and illuminates an indicator light.

On variable electrical power supplies, devices should be provided to limit output to the allowable system voltages or currents (or both). Ground-support equipment should be designed for maintainability and for ease of component replacement.

Capacity requirements should be evaluated, and allowance should be made for growth or expansion of system requirements. This consideration should be reflected in design standards applicable to new procurements.

Safety devices, such as switchguards and safety glass on meters and gages, should be incorporated into the original design. These devices could be incorporated initially at a fraction of the cost for later addition. Periodic system analysis should be performed on each major ground-support-equipment system to ensure that all protective devices are properly sized to protect the spacecraft.

Ground power system. - The use of 28-volt direct-current power for ground instrumentation and control is a good design approach. The power distribution source can be simplified by routing 60-hertz power to each usage area and then converting it to direct current. Facility-supplied power requirements should be defined early to establish the input-power design approach for ground-support equipment.

When 400-hertz power is required, it should be supplied from a facility system. The distribution system should be the same as that recommended in routing 60-hertz power.

Special test equipment. - Two classes of special test equipment should be established. Class 1 should consist of equipment that interfaces directly with the spacecraft or provides power, instrumentation, and servicing functions. Class 1 equipment should require formal configuration control. Class 2 test equipment should consist of all

other equipment (such as diagnostic test tools, special manufacturing devices, and workstands). Class 2 equipment would require minimum configuration control at the using site; changes could be authorized by the resident manager.

Cleanliness and environmental control. - The vehicle cleanliness requirements should be established and thoroughly justified early in the design phase because ground-support-equipment costs increase geometrically as cleanliness requirements become more stringent. During a ground-support-equipment system buildup, acceptable cleanliness must be verified as each component is installed. The final fluid sample must be taken at the ground-support-equipment/vehicle interface. A certified, clean filter should then be installed downstream of the last sample point before servicing. This installation eliminated the need for numerous expensive quick-disconnect fittings used solely for sampling.

Hardware that has environmental requirements should be cleaned to an established level early in its construction, and this cleanliness should be maintained until completion. Personnel should be given cleanliness instruction, and the required cleanliness levels should be posted. Assembly areas should be designed and built as specified clean areas during initial construction.

Automation. - Decisions to determine the ground systems to be automated must be based on a comprehensive review of projected program milestones. Automation is recommended when extensive and complex test and launch operations, such as those encountered during the Apollo Program, must be accomplished within a limited time frame; however, the costs of automation must be carefully weighed against those required to perform relatively simple mechanical tasks manually (such as costs associated with Apollo fluid servicing).

Common-use equipment. - The common-use concept should be considered for projects that involve more than one contractor when identical or similar requirements exist. Contractor capabilities must be evaluated to select a hardware developer that is best suited to provide specific items of common-use equipment. This evaluation should include manpower loading, manufacturing capabilities, procurement procedures, and scheduled work-load considerations.

Management of ground-support equipment and site readiness. - Ground-support equipment site-activation schedules must be coordinated with manufacturing and construction activities and aligned with expected facility-occupancy dates. An automatic schedule-adjustment procedure should be available to compensate for vehicle schedule changes.

Periodic facility technical evaluations should be conducted to ensure that basic requirements (such as size, access, lighting, ventilation, air conditioning, and power sources) keep pace with test-article and checkout-requirement changes. Basic facility interface definitions should be provided early in the program. Adherence to interface control documents should be enforced rigidly.

Vehicle checkout requirements should be integrated with facility and ground-support-equipment support requirements to optimize checkout flow, to reduce total time, and to minimize equipment requirements. Vehicle/ground-support-equipment integrated schematics should be required for use in troubleshooting and normal test operations. These documents must be updated regularly.

Maintenance and overhaul. - Preventive maintenance should be performed on a periodic basis. All contractors and vendors should be required to deliver preventive maintenance procedures and age/life component-replacement data with the end items. Initial procurement of these data is more economical than obtaining them later. When possible, overhauls should be performed in conjunction with major modifications.

Conclusions

Overall, the Apollo ground-support equipment performed satisfactorily. Although problems were encountered in ground-support-equipment operation because of design inadequacies, material and equipment incompatibilities, or manufacturing flaws, no major personnel injuries or test/launch delays were attributed to the ground-support equipment during the 8 years of Apollo Program support.

Lyndon B. Johnson Space Center
National Aeronautics and Space Administration
Houston, Texas, September 25, 1974
914-50-00-00-72

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1. Burtzlaff, I. J.: Apollo Experience Report - Acceptance Checkout Equipment for the Apollo Spacecraft. NASA TN D-6736, 1972.



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